Tropical Cyclone Formation/Structure/Motion Studies

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LONG-TERM GOALS

The long-term goals are to understand how variabilities in the large-scale atmospheric environment influence tropical cyclone track, structure, and intensity characteristics, and define how these influences differ between developing, mature, and decaying tropical cyclones. During the intensification stage of a tropical cyclone, structure and track characteristics can exhibit large variabilities that decrease potential predictability. Furthermore, there are often periods of reduced predictability during the decaying stage of a tropical cyclone. Because decaying tropical cyclones often transitions to a fast-moving and rapidly-developing extratropical cyclone that may contain gale-, storm-, or hurricane-force winds, there is a need to improve understanding and prediction of the extratropical transition (ET) phase of a decaying tropical cyclone. The structural evolution of the transition from a tropical to extratropical circulation involves rapid changes to the wind, cloud, and precipitation patterns. Furthermore, the ET of a tropical cyclone may impact the midlatitude circulation patterns downstream. Therefore, a tropical cyclone throughout its life cycle has the potential for impacting many shore- and sea-based fleet operations.

OBJECTIVES

One objective of this project is to identify the physical mechanisms in the large-scale circulation that act to initiate, maintain, and terminate periods of enhanced or reduced tropical cyclone activity over the western North Pacific. If reliable forecasts of extended periods of increased or reduced tropical cyclone activity could be made, maritime operations could be coordinated appropriately. Also, improved decision processes with respect to fleet avoidance or sortie could be implemented at increased lead times.

Additional objectives relate to the predictability associated with tropical cyclone formation and extratropical transition. The ability of operational global numerical forecast models to predict the formation of a tropical cyclone is examined. The goal is to provide guidance that conveys a forecast confidence as to whether a specific tropical disturbance will intensify into a tropical cyclone. Structural changes in a mature tropical cyclone are examined as the tropical cyclone moves poleward and begins the ET process. The impacts on predictability are assessed in terms of the increased variability that is introduced into the midlatitude circulation by the ET event and with respect to the predictability associated with the downstream impacts of the ET. The goal is to determine specific aspects of ET that are least predictable by examining forecast characteristics that are most inconsistent among multiple integrations of several operational global numerical models and global model ensemble forecast systems. Also, the structural evolution of the decaying tropical cyclone as it

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transitions from a tropical to extratropical cyclone is examined to identify important environment conditions associated with an ET that may impact operational forecasts of the environmental conditions related to maritime operations near an ET event.

APPROACH

Previous research has identified a potential role of the variability in the large-scale circulation over the Southern Hemisphere on the tropical western North Pacific monsoon trough environment during June-October. The variability in the Southern Hemisphere circulation patterns was examined in the context of the Antarctic Oscillation (AAO). A similar methodology was used to examine the impact of variability in the Southern Hemisphere circulation patterns on the environment of the tropical Atlantic. The hypothesis is that circulations in the Southern Hemisphere propagate toward the equator and force changes in the large-scale circulations over the tropical Atlantic. Induced changes in the large-circulation then impact the growth and decay of African easterly waves (AEWs). A lagged regression analysis is used to examine the relationship between large-scale circulation anomalies over the Southern Hemisphere (predictor) and the zonal winds between Eq.-10^{o}N over longitudes that represent the main development region (predictand) of the tropical North Atlantic. The purpose of this analysis was to examine the influence on the growth/decay characteristics of the AEWs in this region. A second lagged regression analysis was conducted to assess the relationships between the large-scale Southern Hemisphere circulation anomalies and the western Africa monsoon. The purpose of this analysis was to examine the influence on the forcing of AEWs that move westward off the western coast of Africa.

To explain the variation in temporal clustering due to primary large-scale, slowly-varying atmospheric circulation patterns such as the Madden-Julian Oscillation (MJO), a hierarchical framework of global-scale intraseasonal circulations and regional-scale monsoon trough variability is defined. The influence on the slowly-varying atmospheric circulations on tropical cyclone activity is examined for each Northern Hemisphere basin that contains tropical cyclones. The hypothesis is that large-scale, slowly-varying circulation patterns should force a temporal clustering of tropical cyclone activity. An objective scheme is used to provide an estimation of the statistical significance in the amount of temporal clustering of tropical cyclone activity.

Forecasts of tropical vortices made by the National Centers for Environmental Prediction Global Forecast System (GFS), the United States Navy Operational Global Atmospheric Prediction System (NOGAPS), and the United Kingdom Meteorological Office Global Model (UKMO) are analyzed with respect to physical quantities that are relevant to tropical cyclone formation. While summarizing statistics such as false alarm rates and probability of detection are readily identifiable from the database, the potential for correct forecasts of tropical cyclone formation in each model is assessed. The set of fourteen parameters is subjected to a discriminant analysis to examine the most relevant parameters that correctly identify a potential for intensification of a tropical vortex to a tropical cyclone. To place the analysis in a probabilistic framework, the discriminant analysis is applied with a fuzzy methodology such that each physical parameter is assigned a coefficient such that a weighted linear combination of parameters best identifies the potential for tropical cyclone development given the forecast parameters. This type of analysis is made possible by the objective identification and catalog of model parameters relevant to each tropical vortex. This procedure allows for continuous assessment of model performance with respect to a variety of parameters and vortices. Based on the comprehensive database, the discriminant analysis is able to consolidate a comprehensive set of

parameters for the purpose of assessing the development potential given the forecast associated with each new tropical vortex. A comparison of each model's ability to correctly identify tropical vortices that develop into a tropical cyclone will be presented.

Identification of the contribution of MJO and similar slowly-varying atmospheric features, such as equatorial Rossby waves, on tropical cyclone activity has direct bearing on the ability to extend the decision-making process for optimum ship routing and sortie applications. This decision process has been modeled in a dynamic context by which the standard action or no action decision is augmented with an option to wait for new information. The new information is assumed to be a more accurate forecast. The poleward movement and extratropical transition (ET) of a tropical cyclone (TC) initiates complex interactions with the midlatitude environment that often results in a high-impact midlatitude weather system with strong winds, high seas, and large amounts of precipitation. Although these extreme conditions severely impact the region of the ET, there are significant impacts downstream of the ET event due to the excitation of large-scale propagating Rossby wave-like disturbances. The approach to the primary scientific issues associated with ET and downstream impacts due to ET events is to define a framework of mechanisms, predictability, and strategies for increasing predictability. The ET process may be characterized by complex physical interaction within three interrelated regions (Fig. 1). To understand the impact of ET on high-impact downstream weather events, mechanisms responsible for the generation, intensification, and propagation of the Rossby wave-like disturbances need to be identified. All three regions of the ET process likely play important roles in the mechanisms responsible for downstream impacts due to ET. A Rossby wave response may be forced by advection of vorticity due to the divergent wind, which may result from the tropical cyclone core. A similar mechanism may be associated with diabatic Rossby waves due to upward motion along sloping isentropic surfaces that exist at the tropical cyclone-midlatitude interface. Finally, the midlatitude impact region provides the avenue by which the wave energy influences the midlatitude circulation into which the decaying TC is moving. Furthermore, the downstream response to ET events exhibits large spatial and temporal fluctuations, which may be related to specific characteristics of each of the three ET regions. Data from polar-orbiting satellites have been utilized to provide a representation of the structural evolution of the thermal, wind, and precipitation fields during an ET event. A representative ET case was chosen in a pilot study of the structural changes in thermal and precipitation fields during the ET. The microwave data were examined in context with operationally derived model analyses.

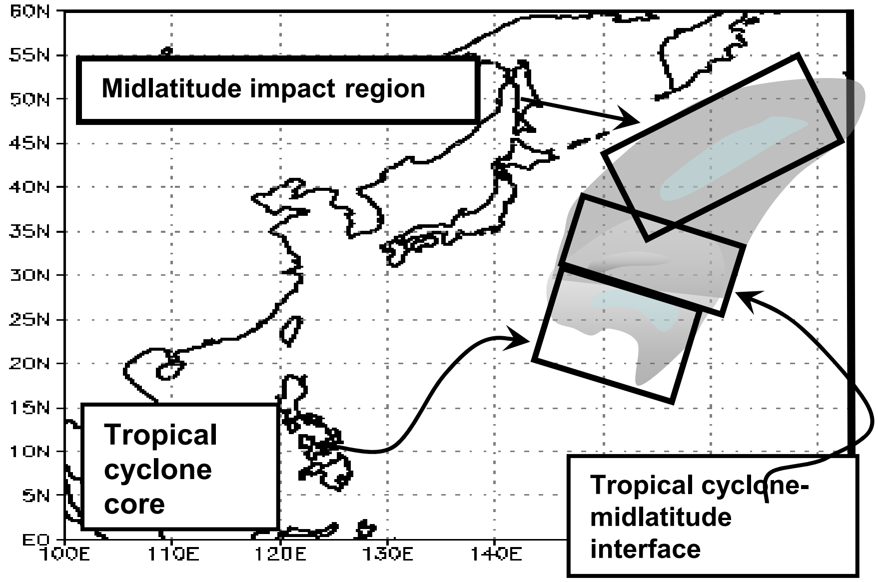

Figure 1: Schematic depiction of three regions associated with the ET of a decaying tropical cyclone over the western North Pacific. The light gray shaded region represents overall cloud patterns. Shaded regions within the light gray areas indicate regions of concentrated cloud amounts defined by convection in the tropical cyclone core region, large-scale precipitation in the tropical cyclone midlatitude interface region, and cirrus in the midlatitude impact region.

WORK COMPLETED

An empirical orthogonal function (EOF) analysis was applied to upper- and lower-level streamfunction and velocity potential fields over the Southern Hemisphere between 1979-2004. A lagged linear regression analysis was then applied to identify the time-varying relationships between large-scale circulations and zonal winds over the main development region of the tropical North Atlantic and outgoing longwave radiation (OLR) anomalies over the region of the West African monsoon.

A fuzzy linear discriminant analysis (LDA) was applied to a database of tropical disturbances defined in analyzed and forecast fields of the NOGAPS, GFS, and UKMO models. Based on the results of the LDA applied to independent data, conditional probabilities were defined to assess the potential for a tropical disturbance to develop into a tropical cyclone given the model forecasts of relevant physical parameters.

A temporal clustering algorithm was applied to time series of tropical cyclone formations over the western North Pacific, eastern North Pacific, and North Atlantic basins. Based on the results of the clustering algorithm, statistically significant periodicities in tropical cyclone formation were identified. A diagnostic analysis of the extratropical transition of Typhoon (TY) Banyan (July, 2005) was performed. In this analysis, a combination of numerically-analyzed fields and data from polar-orbiting satellites was used to examine the changes in structural characteristics of the decaying tropical cyclone. Furthermore, the impact on the downstream midlatitude synoptic-scale circulations was assessed.

RESULTS

Favorable impacts on tropical Atlantic circulation characteristics are defined by an increase in low-level relative vorticity, a decrease in westerly vertical wind shear, and increased convection in the western Africa monsoon (WAM). Both of these conditions imply a favorable environment for development of AEWs over western Africa and their intensification as they move westward over the tropical North Atlantic. The second and third modes of an empirical orthogonal function (EOF) analysis of the 700-hPa height anomalies identify a distinct Rossby-wave pattern.
Significant variability in the Southern Hemisphere mid-latitude circulations is related to the two EOF modes and to equatorward Rossby-wave dispersion.

Formation of a large cyclonic anomaly over the southeast Pacific west of Chile (Figure 2) is related to equatorward propagation of a Rossby-like wave across South America toward the equatorial Atlantic (Rosencrans 2006; Rosencrans and Harr 2006). The cyclonic anomaly precedes westerly wind anomalies over the equatorial North Atlantic by two days. The intensity of AEWs, which is measured by the square of the 850 hPa meridional winds, throughout the tropical Atlantic is found to be enhanced (Table 1) when the equatorial westerly anomalies increase due to forcing from the Southern Hemisphere. Although the AEW intensities increase in approximately 77% of the events, tropical cyclone formation occurred in only 10% of the cases. This is because other factors such as vertical wind shear also impact the potential for an AEW to intensify into a tropical cyclone.

The analysis of a large database of analyzed and forecast tropical disturbances using a fuzzy LDA (Cowan 2006; Cowan et al. 2006; Pasch et al. 2006) provided the ability to construct conditional probabilities of tropical cyclone formation given forecasts of certain physical parameters (e.g., vertical wind shear, mid-level warm core, low-level vorticity). Conditional probabilities defined the likelihood for a tropical disturbance to develop or not develop into a tropical cyclone. Probabilities of tropical cyclone formation exhibited significant skill (Figure 3) over all forecast intervals for all models. However, the degree of skill varied among models such that the ability of the UKMO model to predict formation exceeded that of the GFS and the NOGAPS models. The increased skill in the UKMO model was attributed to accurate representations of the large-scale environment and the thermodynamic characteristics associated with the tropical disturbance.

The period between June-October 1979-2004, contained significant MJO activity (Harr 2006). The temporal clustering algorithm was applied to these years to determine if there was a significant intraseasonal clustering of tropical cyclone activity that would be associated with the intraseasonal variability in the large-scale environment due to the MJO activity. Five of the ten years with significant MJO activity contained significant clustering of tropical cyclone activity on intraseasonal time scales (Figure 4). The clustering of tropical cyclone activity was due to the reduction in tropical cyclone activity during periods when the inactive convection phase of the MJO was over the western North Pacific (Figure 4a) . For the five years in which there was no clustering of tropical cyclone activity (Figure 4b), the inactive convection phase of the MJO did not result in a decrease in tropical cyclone activity. Therefore, the MJO impacts tropical cyclone activity over the western North Pacific by forcing periods of enhanced inactivity.

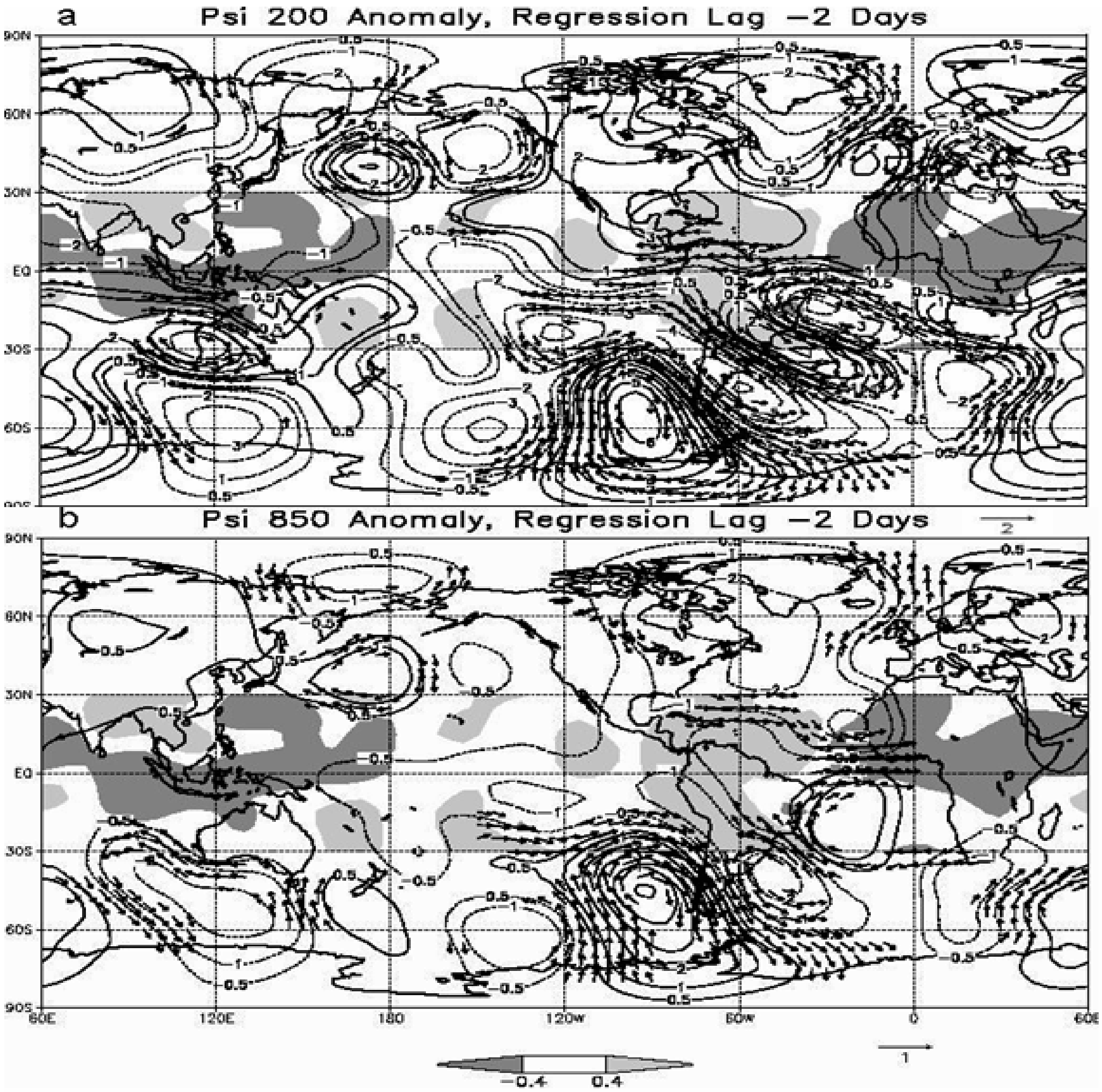

Figure 2: (a) Streamfunction anomaly at 200-hPa (10^6 m^2 s^{-1}) and OLR (W m^{-2}) anomalies in the 10-30-day band during June-Oct 1979-2001 associated with a zonal wind anomaly of +1 standard deviation in the base region 0-10°N, 60°W-10°W. Wind vectors are plotted where the local correlation coefficient is significant at the 95% confidence limit. OLR anomalies are shaded according to the color bar. Reference wind vector is in the bottom right corner.
(b) As in (a), except for 850 hPa.

Table 1. Summary statistics for the relationships between 850-hPa zonal wind anomaly (U') in the base region 0-10°N, 60°W-10°W and OLR anomalies over West Africa events with wave activity (V^2) and TC formation in the tropical Atlantic

Year	U' & OLRA Events	U' & OLRA Events with significant V2	% of events with significant V2	Total TC Formations	TC Formations in U'/OLR' event	TC Formation in U'/OLRA/V^2 event	% TC in U'/OLRA/V^2 event
1979	1	1	100.00	5	0	0	0.00
1980	2	0	0.00	5	0	0	0.00
1981	5	5	100.00	4	0	0	0.00
1982	2	2	100.00	1	1	1	100.00
1983	1	1	100.00	0	0	0	No TC
1984	2	2	100.00	3	0	0	0.00
1985	5	4	80.00	1	0	0	0.00
1986	1	1	100.00	1	0	0	0.00
1987	2	1	50.00	4	0	0	0.00
1988	2	2	100.00	8	0	0	0.00
1989	2	2	100.00	7	1	1	14.29
1990	3	2	66.67	8	2	2	25.00
1991	5	4	80.00	1	1	1	100.00
1992	2	2	100.00	1	0	0	0.00
1993	2	2	100.00	4	0	0	0.00
1994	3	2	66.67	3	0	0	0.00
1995	2	1	50.00	9	1	1	11.11
1996	4	3	75.00	8	3	2	33.33
1997	4	1	25.00	1	0	0	0.00
1998	2	1	50.00	7	0	0	0.00
1999	3	3	100.00	5	2	1	20.00
2000	1	1	100.00	7	2	0	0.00
TOTAL	68	43	78.70	89	13	9	10.11

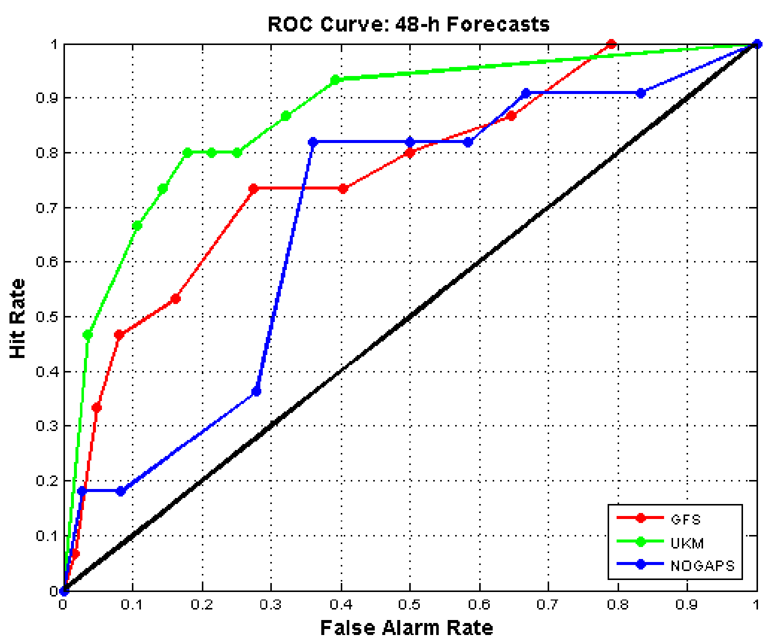

Figure 3. Relative Operating Characteristic curves for 48-h forecasts of the probability of a tropical disturbance intensifying into a tropical cyclone for three operational global models (see inset).

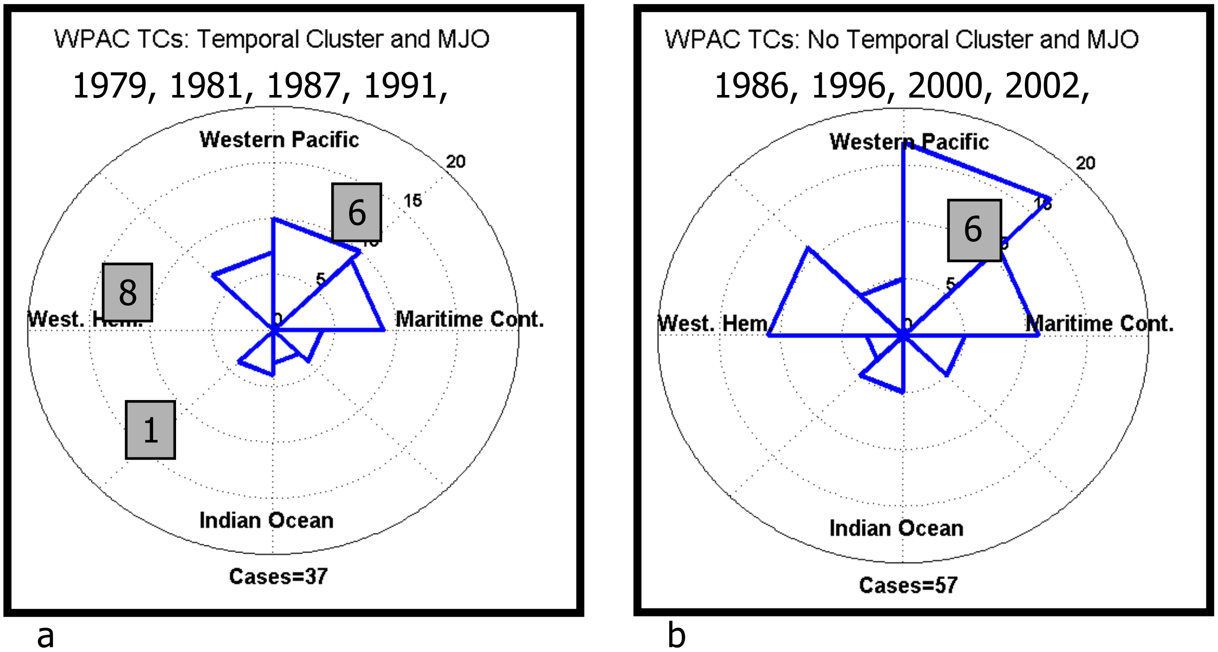

Figure 4. Histogram of the number of tropical cyclones that occurred during eight phases of the MJO during years with significant MJO activity and (a) significant temporal clustering, and (b) no significant temporal clustering of tropical cyclone activity. The labels in the cardinal directions of each polar plot define the location of the active convection phase of the MJO during that phase. Phase 6 contains a significant increase in tropical cyclone activity in both sets of year. There is a significant lack of tropical cyclone activity in phases 1 and 8 during years with temporal clustering.

Identification of the potential for accurate forecasts of tropical cyclone formation by operational global models and the recognition of factors that may affect lower-frequency variability in tropical cyclone activity impact the ability to increase the lead time in the decision process associated with shore- and sea-based fleet activities. Application of a dynamic decision model to a simulated hurricane landfall at Norfolk, VA (Regnier and Harr 2005) identified that there could be as much as an 8% savings in total expected costs if the decision process was optimized in relation to the value of the forecast information, which was assumed to increase as the lead time to the landfall decreased.

Although the ET of TY Banyan (July, 2005) did not result in an extremely intense midlatitude cyclone, the movement of the decaying tropical cyclone into the midlatitudes strongly influenced the downstream synoptic-scale circulation (Figure 5). A pronounced Rossby wave-like response propagated downstream of Banyan in association with a large mid- to upper-tropospheric anticyclone that formed immediately east of the decaying tropical cyclone. The thermodynamic and dynamic mechanisms associated with the formation of this anticyclone were examined using analyzed potential vorticity fields and temperature data derived from polar-orbiting satellites (Vancas 2006). The presence of warm, moist air advected to the east of the tropical cyclone (Figure 6a) caused the low-level warm anomaly to be shifted east of the tropical cyclone (Figure 6b). The combination of the eastward shift in the low-level anomaly with the remnant mid-tropospheric warm anomaly of the decaying tropical cyclone led to a pronounced tilt in the thermodynamic structure during the ET

process. Furthermore, the advection of warm, moist air advected poleward to the east of Banyan contributed to a diabatic redistribution of potential vorticity that contributed to a low-level positive potential vorticity anomaly and an upper-level negative potential vorticity anomaly associated with the large anticyclonic circulation to the east.

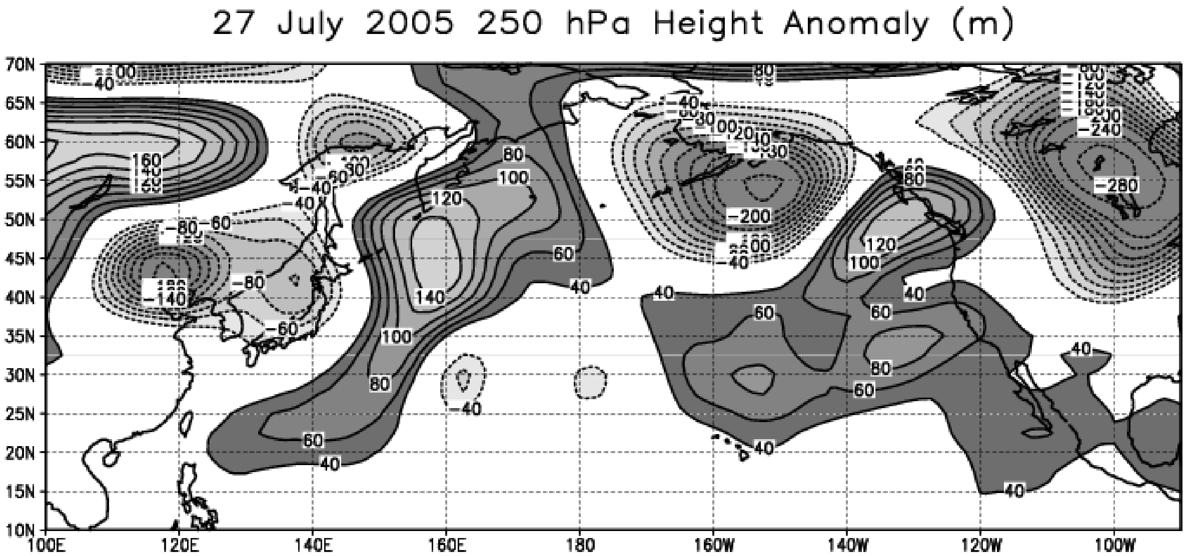

Figure 5. Height anomalies (m) at 250 hPa for 1200 UTC 27 July 2005. The location of TY Banyan is marked by the tropical cyclone symbol

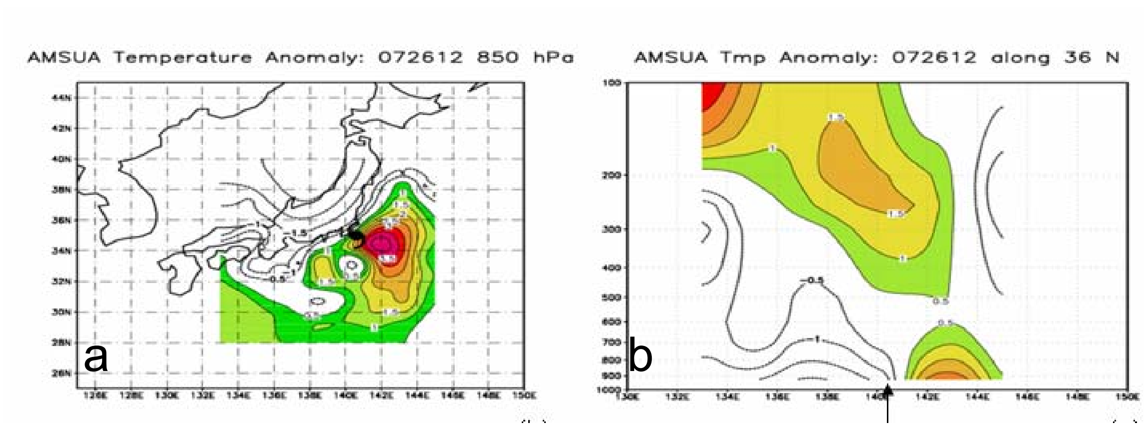

Figure 6. AMSU temperature anomaly (K) from the Advanced Microwave Sounding Unit at 1200 UTC 26 at (a) 850 hPa, and (b) vertical cross-section along 36° N. The arrow along the abscissa of (b) indicates the position of the storm center.

IMPACT/APPLICATIONS

Identification of the interactions between various modes of tropical circulation variability will lead to a statistical forecast scheme of extended periods of tropical cyclone activity/inactivity. Furthermore, the MJO influences tropical cyclone activity over the western North Pacific mostly by forcing extended periods of inactivity. If reliable forecasts of extended periods of inactivity (i.e., at least 20 days with no tropical cyclones) could be made, maritime operations could be coordinated to take advantage of the period of reduced threat from tropical cyclones. Additionally, implementation of dynamic decision processes in would also allow for effective use of additional information by which significant cost savings could be realized.

As characteristics and identification of the predictability associated with operational forecast model characteristics with respect to ET become identified, guidance to operational forecasters will be available such that increased value from numerical products will be realized. Finally, accurate probabilistic forecasts of tropical cyclone formation conditioned on parameters that are analyzed and forecast by operational global models will provide for increased utility for long-range planning of operations in regions over which tropical cyclones tend to form.

TRANSITIONS

It is anticipated that an operational forecast scheme of intraseasonal variability in tropical cyclone activity will be based on the research results from this project. An assessment of the potential for accurate forecasts with respect to ET circulations will be available to operational forecasters. Systematic examination of microwave data during the ET of tropical cyclones will lead to use of a pattern analysis by forecasters to diagnose the important structural changes during the ET process. Probabilistic forecasts of tropical cyclone formation could be automated via interaction with the database of model forecast parameters.

RELATED PROJECTS

The work being completed on the structural changes and downstream impacts during ET is related to a project titled The predictability of extratropical transition and of its impact on the downstream flow under the direction of Dr. Sarah Jones.

SUMMARY

Significant progress on important aspects of tropical cyclone formation, structure change, and extratropical transition has been made over the past year. The approach has been to examine important physical processes in a multi-scale framework. Several important results have direct bearing on shore- and sea-based fleet operations with respect to sortie and operation planning purposes.

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